

The most distant compact groups

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Received _____; accepted _____

To appear in Ap. J. Lett.

ABSTRACT

We present photometric and spectroscopic observations of the members of three previously cataloged compact group (CG) candidates at redshifts $z > 0.3$. These confirm spectroscopic redshifts compatible with being gravitationally bound structures at redshifts 0.3112, 0.3848 and 0.3643 respectively, and then they are the most distant CGs known with spectroscopic confirmation for all their members. The morphological and spectroscopic properties of all their galaxies indicate early types dominated by an old population of stars, with little star formation or nuclear activity. Most of the physical properties derived for the three groups are quite similar to the average properties of CGs at lower redshifts. In particular, from the velocities and positions of the respective members of each CG, we estimate short dynamic times. These leave open the questions of identifying the mechanism for forming CGs continuously and the nature of the final stages of these structures.

Subject headings: galaxies: kinematics and dynamics — galaxies: groups: individual — galaxies: evolution — galaxies: distances and redshifts

1. Introduction

Compact groups (CGs) of galaxies are defined as relatively dense associations of four or more galaxies that are isolated from larger structures. Spectroscopic observations of their members show that typical velocity dispersions of such systems are $\sim 200 \text{ km s}^{-1}$. Although the presence of contaminant interlopers is unavoidable in some cases, the detection of hot intergalactic gas X-ray emission (Ponman et al. 1996) in 75 % of the systems and intragroup diffuse light (Nishiura et al. 2000; White et al. 2003; da Rocha & Mendes de Oliveira 2005; da Rocha et al. 2008) indicate that most CGs are indeed real physical associations.

Since the first catalog of CGs by Hickson (1982), many other catalogs have been built from different surveys (Iovino et al. (2003); de Carvalho et al. (2005); Prandoni, Iovino, & MacGillivray (1994); Iovino (2002); Focardi & Kelm (2002); Barton et al. (1996); Allam & Tucker 2000). Particularly relevant for this paper are the SDSS-based catalogues (Lee et al. (2004); McConnachie et al. (2009), hereafter MC09). Those catalogs have been built using basically the criteria established originally by Hickson (1982) based on the number of galaxy members (≥ 4) within some specific magnitude range, a given isolation criterion in order to avoid considering CGs as transient or projected associations of galaxies within larger structures, and compactness. The exact values of such parameters must be selected in order to get an optimum balance between completeness and the presence of foreground or background contaminants. The fraction of contaminants present in a given catalog depends critically on the value adopted for the surface brightness of the CG, as was explicitly demonstrated by MC09.

The SDSS-based catalogs have allowed for the first time the detection of a large number of CG candidates at redshift $z \geq 0.2$. In particular, MC09 have compiled two different catalogs containing 2,297 (catalog A) and 74,791 (catalog B) CG candidates, imposing limits for their members of $r = 18 \text{ mag}$ and 21 mag respectively. The mean number of

galaxies per CG candidate is 4.2 (i.e., most of the candidates have four galaxies). The fraction of CG candidates with a spectroscopic determination of redshift is 44 % and 18% for catalogs A and B respectively.

There are 2,062 CG candidates at estimated redshift $z > 0.3$ (the most distant has $z = 0.46$) in MC09 (catalog B). Therefore, the MC09 catalog B provides a representative sample of candidates and allows for the first time the exploration of the physical conditions in CGs through the past ~ 5 Gyr. For the great majority of the CG candidates, the spectra of just one galaxy was obtained by SDSS. To reduce the degree of random projected associations, we restricted our study to the 23 systems with at least two members with concordant determination of spectroscopic redshifts at $z > 0.3$. Here, we present the results for three such candidates¹ at redshifts 0.31 (MC4629), 0.38 (MC7697), and 0.36 (MC13069).

This paper is organized as follows: after this introduction, Section 2 presents the basic issues of the observations and data processing, while the redshift estimations and the main observational properties are considered in Section 3. Section 4 presents the main kinematic and dynamical properties. The main conclusions are presented in Section 4.

2. New observations and data reduction

Table 1 presents a summary of the photometric and spectroscopic observations presented in this paper. Using the 2.5 m INT (ORM, La Palma, Spain), images of a field centred in each of the three CG candidates were obtained. The images were bias subtracted,

¹Throughout this paper we name the CGs as MC followed by the same number used in the MC09 catalog B.

flat field corrected and combined using IRAF². The images for the CG candidate MC4629 were taken in photometric conditions, whilst during the observations of MC7697 and MC13069 there was evidence for the presence of some high clouds. An approximate photometric calibration was done by comparing with the corresponding SDSS images in the r filter. The $1\text{-}\sigma$ brightness fluctuation of the resulting images is $27.0\text{--}27.5\text{ mag arcsec}^{-2}$.

The spectroscopic observations were taken at the 10.4 m GTC (ORM, La Palma, Spain). Details of the telescope and the instrumental configuration can be found on the telescope web site (www.gtc.iac.es). We used the OSIRIS spectrograph with the R1000B grism. The observations were carried out in August 2010 in service mode. A single position of a long slit crossing the two members of each CG candidate with unknown redshift was taken. The spatial sampling was 0.25 arcsec/pixel . The slit width was 1 arcsec . The nights were clear with traces of dust and light cirrus. For wavelength calibration, we used HgAr and Ne lamps taken at the end of each night. The stability of the wavelength calibration during the night was checked with the main sky lines. The effective spectral resolution was 7 \AA . The spectra were analyzed following a standard procedure using IRAF, which comprises bias subtraction, flat field correction, coaddition of exposures of the same field, wavelength calibration, and extraction of the spectra. The flat field correction was done only in the red part of each spectrum due to the low response of the calibration lamp in the blue part (this correction is $\sim 1/200$). The spectral calibration provides a sampling of 2.07 \AA and is quite accurate ($\sim 0.05\text{ \AA}$), as checked through the position of the atmospheric OI line. We used standard spectroscopic stars from the catalog by Oke (1990) to correct for the response of the configuration at different wavelengths. This does not provide an absolute

²IRAF is the Image Reduction and Analysis Facility, written and supported by the IRAF programming group at the National Optical Astronomy Observatories (NOAO) in Tucson, Arizona.

flux calibration owing to the conditions of the observations, the different orientation of the slit width, etc. We did not correct for the telluric band at 7600 Å.

3. Membership and environment

Figure 1 shows images of each CG candidate and the extracted spectra of their members (for completeness, we also include the spectra of the galaxies observed with SDSS). The galaxies labeled 1 to 4 in each plot are those used to define and characterize the three CG candidates. Galaxies 1 and 2 are those for which SDSS spectra exist and were used by MC09 to estimate the redshift of the CG candidate, whilst galaxies 3 and 4 are those targets that have been confirmed as members with the new observations presented in this paper. The extracted spectra have $\text{SNR} \sim 12\text{--}18$ per pixel at a spectral position around 6500 Å with the exception of MC4629-3 (the brightest object of the sample observed with the GTC), which has $\text{SNR} \sim 50$ per pixel. The spectra of all the galaxies are dominated by typical galactic absorption features. A minimum number of five absorption lines was identified in the spectrum of each galaxy; the most important being CaII H&K, MgI, the G-band, H_β , and, in some cases, NaI and H_α ; the presence of these spectral features is enough for a reliable determination of redshift. This was done³ by cross correlating their spectra with several synthetic, galactic, and stellar templates (Tonrey & Davies 1979). The results from all these methods were consistent, although the best accuracy was obtained using two stellar templates of spectral class G and K obtained from the list provided by SDSS. The redshifts determined by this method are the ones quoted in Table 2. The R factor for those determinations (Tonrey & Davies 1979) ranges from 5 to 15. The spectral

³For consistency, we determined the redshift also for the targets with previously measured redshift in SDSS.

calibration introduces an additional $\sim 3 \text{ km s}^{-1}$ uncertainty. Table 2 lists the identification of each galaxy (col. 1), its equatorial coordinates (cols. 2 and 3), r magnitude (col. 4), $g - r$ color (col. 5), spectroscopic redshift and statistical uncertainty (cols. 6 and 7), and R factor (col. 8). The main conclusion obtained from the spectra is that all the galaxies proposed as members of the respective CG candidates have concordant redshifts. In other words, we confirm that the three CG candidates are real in the usual meaning of the term. Their estimated redshifts are 0.3112, 0.3848, and 0.3643 for MC4629, 7697 and 13069 respectively.

The morphological analysis of galaxies at redshifts ~ 0.3 is limited from ground based images. In fact, at the distances of the three CGs, the spatial scales are 4.53, 5.21, and 5.05 kpc arcsec $^{-1}$ for MC4629, MC7697, and MC13069 respectively⁴. Nevertheless, none of the CG candidates shows conspicuous signs of interactions and/or major distortions.

None of the galaxies shows evidence of significant star formation or AGN activity. Only in the case of the galaxies MC7697-3 and MC7697-5 (this object was not included as member of the CG in MC09; however we took a spectra that allow to determine a redshift concordant with being a member of the CG, see below) tiny lines of $[OII](\lambda 3727) \text{ \AA}$ were detected. So, the morphological and spectroscopic analysis of the galaxies in the three CGs, shows that all the members are old ellipticals. The absence of galaxies with emission lines contrasts with what is found in Hickson CGs. In fact, several authors (e.g., Martinez et al. 2010 and reference therein) have studied samples from Hickson CGs and found that 60–70% of all the galaxies have emission lines. About one quarter and one third of such emission is due to AGN and star formation activity respectively.

The criteria imposed to select the CG candidates by MC09 are basically the same as

⁴Throughout this paper we adopt a standard lambda cold dark matter model with $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$; $\Omega_M = 0.27$, and $\Omega_\Lambda = 0.73$).

those adopted for Hickson’s sample. However, owing to the fact that the sample of galaxies used by MC09 is limited to those objects with $r < 21$ mag, the criteria of isolation as defined in that paper can be only applied for those candidates as MC4629 in which the brightest galaxy has $r < 18$ mag. We have checked that extending the sample of galaxies considered in the SDSS photometric survey up to $r = 22$ mag, neither MC7697 nor MC13069 strictly follow the isolation criteria. In the case of MC7697 there is a galaxy about 2 mags fainter than the brightest galaxy of the group at ~ 22 arcsec from the center of the group. For MC13069 there are several nearby objects within a range of 3 mags from the brightest galaxy of the group. We studied also the density of objects in the near environment of each of the three groups. Fig. 2 presents the projected density of galaxies in r -band SDSS images (the results obtained are similar analyzing the INT images) as a function of the distance to each CG candidate. Only objects catalogued as galaxies in SDSS with magnitudes $r < 22$ and photometric error < 0.2 mag have been considered for that plot. The mean densities of galaxies at distances between 1 and 2 Mpc from each candidate, are 43, 38 and 46 gal Mpc $^{-2}$ for MC 4629, MC7697 and MC13069 respectively. The members of MC4629 and MC13069 seem to be immersed in a overdense region of ~ 1 Mpc. So, two out of the three CGs analyzed here, are embedded in a rich environment. These results, although not statistically significant, are compatible with the findings by Mendel et al. (2011) in their analysis of the MC09 (catalog A).

A brief description of the specific properties of each group is presented below:

- MC4629: Galaxies MC4629-1, MC4629-2, and MC4629-3 have absolute magnitudes in r in the range -22 to -23 mag. The projected separation between MC4629-1 and MC4629-3 is ~ 5 arcsec (~ 23 kpc), whilst their difference in radial velocity is 420 km s $^{-1}$. Although there are no significant morphological distortions, both galaxies are slightly elongated and seem to be immersed in a halo with an extension of ~ 90

kpc at least that comprises also the galaxy MC4629-4. There is an extended X-ray source (Vikhlinin et al. 1998) at 20 arcsec (~ 90 kpc) from the optical center of the CG, and having a core radius of 34 ± 13 arcsec and a flux $(12.1 \pm 2.8) \times 10^{-14}$ erg s $^{-1}$ cm $^{-2}$ that corresponds to a luminosity of 3.5×10^{43} erg s $^{-1}$. That X-ray luminosity is higher than the values measured in local CGs and is in the typical range of clusters of galaxies.

- MC7697: There is more diffuse material in this group than in MC4629. Galaxies MC 7697-1 and MC7697-3 are separated by ~ 6 arcsec (~ 30 kpc). The image shows some evidence of distortion of the outer isophotes of both galaxies and the existence of a bridge of light connecting them and extending out towards NW. We interpret this as indicative of interaction between those two galaxies. For the object labeled 5 (see Fig. 1b) we determined a redshift of 0.38525, thus confirming that the object is also a member of the group. Objects MC7697-2 and MC7697-5 seem to form part of a group of four objects immersed in a region ~ 60 kpc \times 45 kpc. There is a cataloged SDSS cluster (Goto et al. 2002) at 0.151 arcmin for which these authors identified 11 objects as potential members.
- MC13069: The group is dominated by galaxies MC13069-1 and MC13069-2 which are separated by ~ 20 kpc; however, this proximity does not produce major distortions apart from an asymmetry in galaxy MC13069-1 through the NE. The velocity dispersion (Table 3; col. 3) of this group is within the range found for massive clusters of galaxies. This high velocity dispersion is basically due to galaxy MC13069-2. The absence of major distortions might indicate that this galaxy is experiencing the first stages of interaction with MC13069-1.

4. Physical properties

The radial velocity dispersion, their random errors, and the intrinsic three - dimensional velocity dispersion (Hickson et al. 1992) are listed in Table 3; cols 3 - 5. To estimate masses of large structures, several estimators have been proposed (Heisler et al. 1985) and can be applied to the specific case of CGs (Hickson et al. 1992). Here, we only compute the virial masses (Table 3; col. 8); of course that estimate is only reliable when the group is in virial equilibrium. As expected from the velocity dispersions, the masses found for the CGs MC4629 and MC7697 are within the range of virial masses of local CGs estimated by Hickson et al. (1992); whilst MC13069 has a similar mass to that found in rich clusters of galaxies.

The velocity dispersion and masses obtained for MC13069 are consequence of the difference in velocity between this galaxy and the other members of the group; if we exclude this galaxy from such estimations⁵, the values obtained are 281 km s^{-1} and $\log(M) = 46.03$ for the velocity dispersion and mass respectively. Both values would fall within the expected range of values for CGs.

The crossing times (Table 3; col. 7) are quite short (a few hundredths of the age of the Universe), and below $\sim 1/20$ of their cosmological distance. The dynamic crossing times $\log H_o t$ for the Hickson sample are within the range $-2.96, +0.94$, with the majority of the CGs having values within -2.5 and -1.5 . The median of that sample was $\log H_o t = -1.80$ ⁶. The $\log H_o t$ values estimated for our three groups are -1.76 , -1.86 , and -2.32 , which are within the range spanned by most of the CGs in the Hickson sample. The values found for

⁵The remaining three galaxies would not obviously fit the criteria for a CG.

⁶Those authors used $H_o = 100 \text{ km s}^{-1}\text{Mpc}^{-1}$; correcting to the value of the Hubble constant adopted in this paper, we get $\log H_o t = -1.95$

the three CG analyzed in this paper agree also with those found by Pompei et al. (2006) in their study of several CGs at redshift ~ 0.12 .

These short crossing times seem to indicate that, unless a mechanism for stabilization and/or acquisition of new members is established, the three CGs presented here could not have lasted until the present, and so the population of CGs at redshifts ~ 0.3 is different from the local one. This raises the issue of the generation and fate of CGs. The most natural scenario (Mendes de Oliveira 2006) would be the transformation of CGs into a relatively isolated single giant elliptical galaxy leaving as an additional tracer the presence of an extended gas halo; these properties match those found for the so-called elliptical X-ray overluminous galaxies or fossil groups. In such systems there is an absence of intermediate bright galaxies; if fossil groups are the final stage of CGs, the lack of intermediate bright galaxies might reflect not only the signature of an evolved stage but also the isolation criteria adopted to define CGs. It is worth mentioning also that the three CG candidates match the trend between masses and crossing times found in Hickson’s sample in the sense of faster evolution for more massive CGs.

Hickson et al. (1992) found weak evidence of anticorrelation between crossing times and the difference in brightness between the two brightest galaxies of each group. Such correlations seem sensible in a hierarchical framework. These differences in magnitudes between the two brightest ranked galaxies in our groups (in the g band and after K corrections) are $+0.32$, $+0.07$, and $+0.07$ for MC4629, MC7697, and MC13069 respectively. These values are smaller than the ones found in Hickson CGs (see Fig. 6 in Hickson et al. 1992); whether this is a consequence of selection bias or reflects some physical characteristic of the CGs will require further investigation. The range in $g - r$ color spanned for the members of each group are 0.85 , 0.51 and 0.17 mag for MC4629, MC7697 and MC13069 respectively. These seem to indicate a more evolved evolutive stage of MC13069.

The range in density, $\log \rho$, spanned for the majority of CGs in the Hickson sample ranges from -25.7 to -22.7, with a mean value of -24.16 g cm^{-3} , so the values found for the three groups analyzed in this paper are within that range. The mass-to-light ratio found for MC13069 is typical of the values found in local CGs; however, for MC4629 and MC7697 the estimated mass-to-light ratios are a bit low as compared to most of the values found in Hickson’s sample and are more typical of those found in single galaxies, which seems to indicate that there is not much intergalactic mass in those two groups.

5. Conclusions

- New observations complemented with available SDSS spectra for all their galaxy members, confirm three candidates as real CGs at redshifts $z = 0.3112$, 0.3848 , and 0.3643 for MC4629, 7697, and 13069 respectively. Then, they are the three most distant CGs known with spectroscopic confirmation of all their members.
- The estimates for the velocity dispersion of MC4629 and 7697 are similar to values found for local CGs, whilst MC13069 has a dispersion typical of a relatively massive cluster of galaxies. This is mainly a consequence of one of the galaxies of this group, which has a difference in velocity with respect to the velocity of the remaining three galaxies of $\sim 1,500 \text{ km s}^{-1}$.
- The galaxy members of the three CGs show an early type morphology. This is confirmed by the spectra, which seem to be dominated by an old stellar population. Two of the CGs (MC4629 and 13069) are immersed in more extended overdense regions.
- The main physical properties derived from the photometry and spectroscopy are very similar to those found in CGs at lower redshifts. The evolution as measured from the

dynamic times is relatively fast in the three cases and thus supports a scenario with continuous formation of CGs.

- Statistical conclusions will require the detection and characterization of a larger sample of CGs; nevertheless the observation presented here points to a scenario in which CGs are relatively transient structures that possibly collapse into single large elliptical galaxy in an environment similar to those found in fossil groups.

We are particularly grateful to E. Díaz-Giménez, who read this manuscript and gave many useful comments and suggestions. We thank to R. Barrena who made the observations at the INT. This paper is based on observations made with the INT and GTC telescopes (ORM, La Palma, Spain). We have used the databases SDSS (<http://www.sdss.org/>) and NED (<http://nedwww.ipac.caltech.edu/>).

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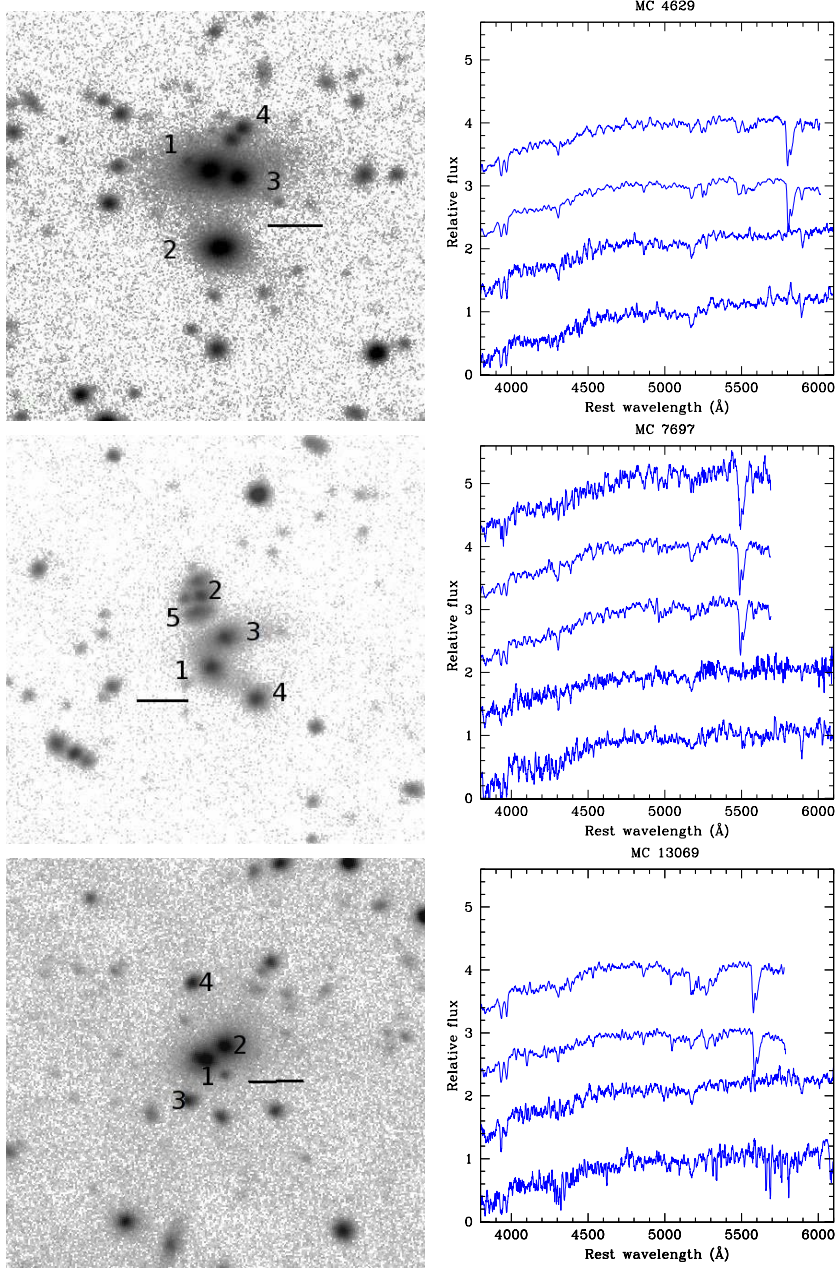


Fig. 1.— (*Left:*) Image of the compact group candidates (from top to bottom) MC4629, MC7697, and MC13069. The horizontal line in the images corresponds to 10 arcsec. (*Right:*) Rest-frame spectra of their galaxy members. The spectra have been normalized with respect to the value at 5000 Å. In each panel, the spectra are plotted starting from galaxy # 1 at the bottom. For visual purposes, all the spectra (apart from the one of galaxy # 1) have been shifted one unit with respect to the precedent galaxy. The spectra of galaxies #1 and #2 were obtained by SDSS.

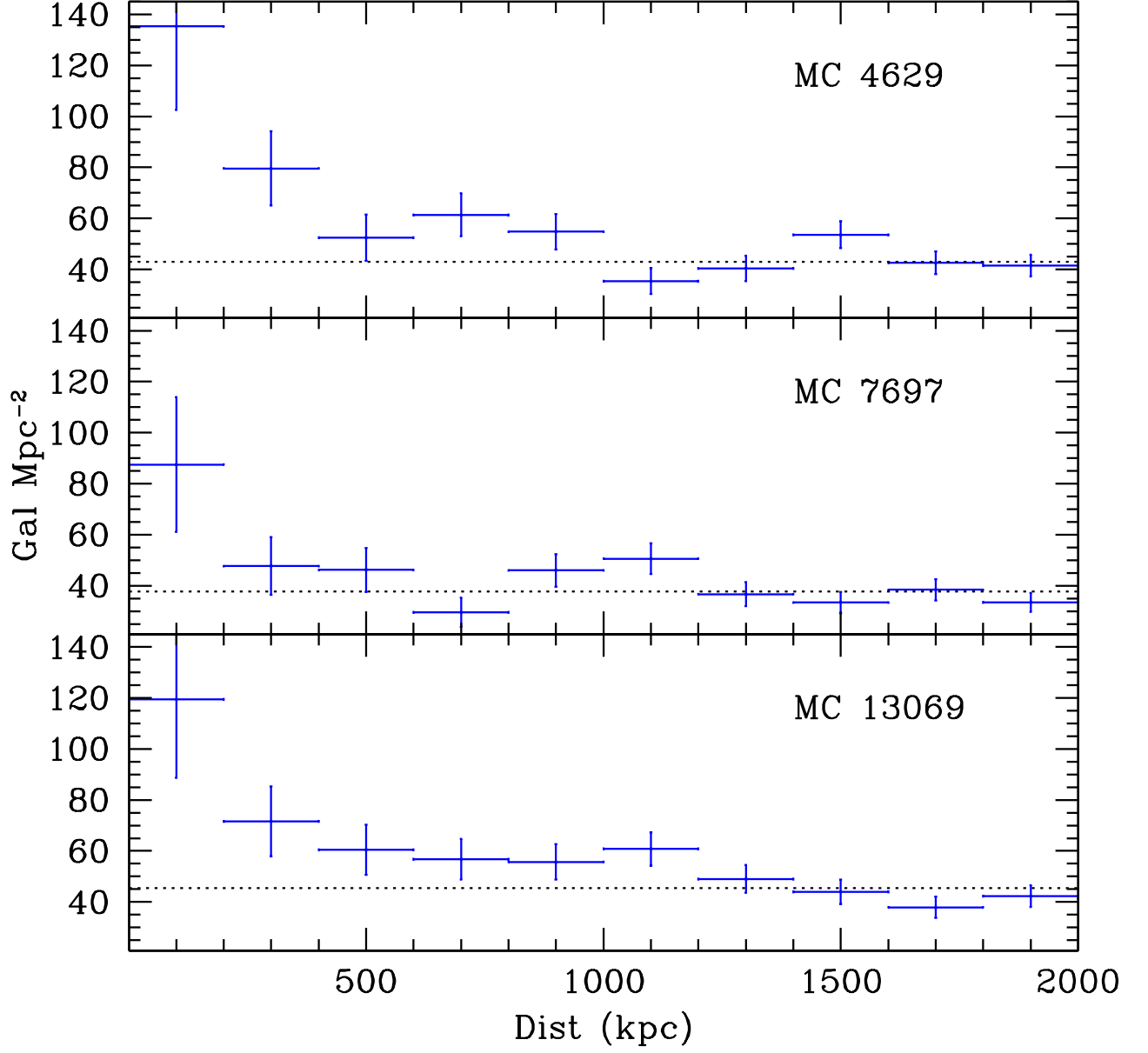


Fig. 2.— Projected density of galaxies in a region centered on each CG candidate. The dotted lines indicate the mean density of galaxies at distances between 1 and 2 Mpc from each group.

Table 1: Observing log

ID	Spectra				Images			
	Date (ddmmyy)	t_{exp} (s)	Seeing (")	Airmass	Date (ddmmyy)	t_{exp} (s)	Seeing (")	Airmass
MC4629	040810	3x1200	0.9	1.51-1.87	240410	3x1200	1.2-1.5	1.12-1.28
MC7697	090810	3x200	1.0	1.61-1.67	250410	3x1200	1.0-1.2	1.35-1.64
MC13069	150810	3x700	0.8	1.22-1.29	250410	3x1200	1.0-1.2	1.16-1.29

Table 2: Members of each compact group

ID	RA (J2000)	Dec. (J2000)	r	$g - r$	z	δv (km s ⁻¹)	R
MC4629-1	16 06 43.8	23 29 15.7	17.86	1.80	0.31172	51	8
MC4629-2	16 06 43.9	23 29 01.7	18.28	1.58	0.31141	60	6
MC4629-3	16 06 43.5	23 29 13.4	18.91	1.32	0.31032	43	12
MC4629-4	16 06 43.3	23 29 21.8	20.34	2.17	0.31142	41	10
MC7697-1	14 17 53.4	01 14 48.9	18.90	1.62	0.38419	55	6
MC7697-2	14 17 53.5	01 15 01.8	19.10	1.50	0.38417	70	6
MC7697-3	14 17 53.2	01 14 54.0	19.12	1.11	0.38478	33	12
MC7697-4	14 17 52.9	01 14 42.7	19.53	1.42	0.38599	30	15
MC13069-1	15 39 10.9	45 33 11.9	18.65	1.73	0.36352	53	5
MC13069-2	15 39 10.5	45 33 14.0	18.72	1.74	0.36814	58	6
MC13069-3	15 39 11.3	45 33 04.9	20.50	1.64	0.36176	32	13
MC13069-4	15 39 11.0	45 33 25.9	20.63	1.57	0.36392	35	12

Table 3: Dynamic properties of each compact group

ID	z	σ	$\delta\sigma$	V	R	$\log (H_0 t)$	$\log (M)$	$\log (M/L)$	$\log (\rho)$
		(km s ⁻¹)	(km s ⁻¹)	(km s ⁻¹)	(kpc)		(g)	(solar units)	(g cm ⁻³)
MC4629	0.3112	160	25	263	50	-1.76	45.45	0.50	-24.74
MC7697	0.3848	222	25	374	57	-1.86	46.07	1.13	-24.29
MC13069	0.3643	703	23	1214	64	-2.32	47.02	2.16	-23.49